Design of an FRP-Reinforced Concrete Beam System for Fire Performance

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ABSTRACT

Concrete members that are reinforced with fibre-reinforced polymer (FRP) have many advantages over traditional steel reinforcement, such as their lack of corrosion, light weight, and electromagnetic transparency. In fire, however, the bond between the FRP reinforcement and the concrete degrades due to resin softening at temperatures around its glass transition temperature. As a consequence of this bond degradation, the means of force transfer between FRP bar and concrete are lost, and a brittle failure results from the loss of the tension reinforcement. This research develops a new arrangement of internal FRP reinforcement that does not rely only upon bond for load transfer. Instead of using straight, separate, FRP bars as reinforcement, closed FRP loops are utilised as the longitudinal reinforcement. Small-scale tests upon single loops of FRP reinforcement are conducted to understand and characterise its behaviour at both ambient and high temperatures. Push-off tests are performed in which the ends of reinforcement loops are embedded inside two concrete blocks. These tests are used to characterise the reinforcement performance at a variety of temperatures. By contrasting the performance of FRP loop reinforced specimens with those containing hooked and straight reinforcing bars, it was demonstrated that the closed loop reinforcement could carry load effectively when subjected to elevated temperature.

INTRODUCTION

Fibre reinforced polymers (FRP) have been used in many civil engineering applications where ordinary steel is not suitable due to high corrosive environment or when structure electromagnetic transparency is required [1]. One of the principal reasons that FRP internal reinforcement is not more widely used is its potentially poor performance in fire, due to the loss of bond between FRP and concrete. Bond provides force transfer between the concrete and the FRP bar. FRP bars are made with different contact surface configurations: sand coated, braided surfaces, spiral pattern, ribbed surfaces, or indented surfaces [2]. Resin plays a vital role in the mechanical behaviour of these surface configurations and it is thus the critical component in the performance of FRP reinforcement at elevated temperature.

The fibres within FRP reinforcement can tolerate high temperatures and continue supporting loads; for instance, carbon fibre is virtually unaffected by temperature up to 1000°C and glass fibre retains most of its strength up to 600°C. When the temperature of the resin exceeds its *glass transition temperature* (T_g), however, its stiffness and strength are greatly reduced, and it becomes viscous due to changes in its molecular structure [3]. Consequently the bond surface is unable to transfer shear and bearing stresses between the bar and the concrete [3]. The resin also allows load sharing between the fibres, but above the glass transition temperature this is lost, leading fibres to become overstressed and eventually break [4].

Bisby et al. [5] reported that the bond strength of FRP reinforcement at 100-200°C degrades to about 10% of its ambient temperature value. Katz et al. [1] observed significant bond degradation at 200°C in pull-out tests on various types of FRP bars conducted at different temperatures, accompanied by softening of the bond response as the temperature increased. Saafi [6] observed that the bond strength of the tested FRP bar was reduced by 50% at 125°C. As a consequence, the bond performance at high temperature is a critical aspect in the design of a structure incorporating FRP as reinforcement [7].

The resistance of a FRP-reinforced concrete element subjected to elevated temperature can be improved if the orage the FRP bars are anchored at in a region not directly exposed to fire; for example, Nigro et al. [8] demonstrated that if the bars are bent up at the end of a member, good structural behaviour can be achieved in fire.

RESEARCH SIGNIFICANCE

This research project investigates a new arrangement of FRP internal reinforcement intended to enhance the fire performance of FRP-reinforced concrete. Instead of using straight separate FRP bars (an arrangement that has been copied from steel-reinforced concrete design), the longitudinal reinforcement is made from closed FRP loops, which are filament wound from long continuous fibres. This design exploits the fact that the FRP fibres are capable of sustaining a large proportion of their original strength at high temperatures. It does not rely only upon bond for load transfer, as load can still be resisted through the loops even if the resin softens. This paper presents the results of a series of push off tests that demonstrate that the reinforcement concept works at elevated temperatures.

EXPERIMENTAL PROGRAM

Push off tests were performance to investigate the performance of the new design of FRP reinforcement at three different temperatures: ambient (≈20ºC), the glass transition temperature of the FRP matrix resin, and at an elevated temperature. A total of eighteen specimens were manufactured and tested under static monotonic loading.

Specimen Design

Each test specimen comprised two concrete blocks (180mm cubes), with carbon FRP (CFRP) reinforcement bridging between the two blocks. This is similar to the test arrangement recommended by in the ACI [9] and Canadian [10] guidelines to measure the capacity of hooked FRP bars and stirrups. Three different types of test specimen were cast, and these are shown in Figure 1.

- Group A specimens contained a filament wound loop of CFRP.
- Group B specimens contained the same closed loop, except that the reinforcement was cut at one end, making the loop within one of the blocks into two hooked bars.
- Group C was the conventional reinforcement arrangement of two straight bars.

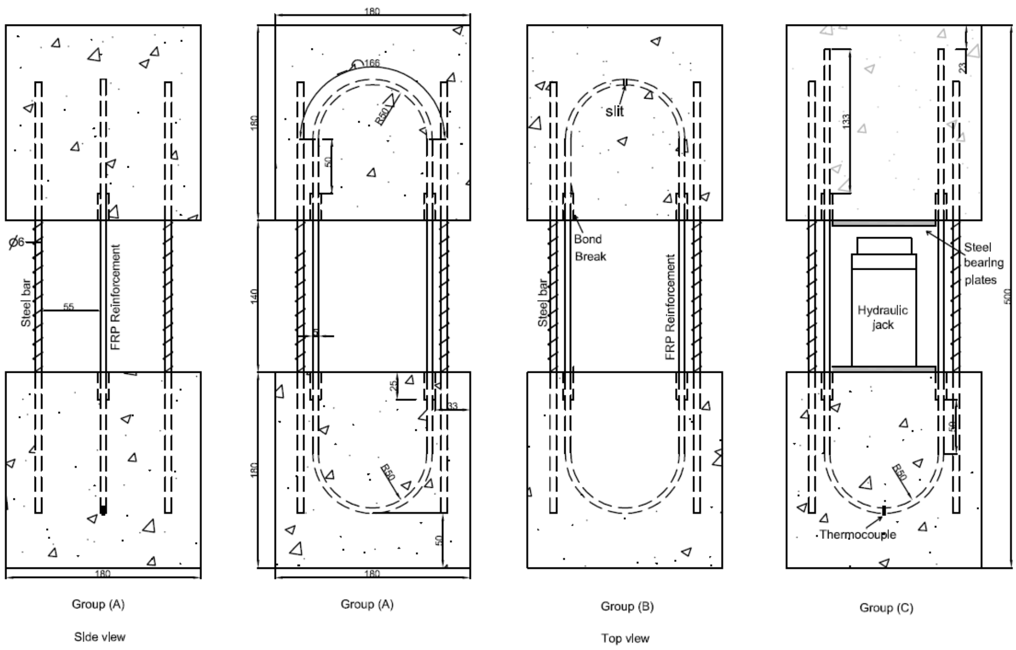

Figure 1. Test specimens
Contrasting the performance of FRP loop reinforced specimens with those containing hooked and straight reinforcing bars, allowed the relative importance of the bond and fibre continuity to be demonstrated.

The CFRP reinforcement had a square cross-section of 5´5mm and a sand-coated surface; its manufacture is described below. The bend radius of the loops was *r* = 50mm (which was governed by the size of specimen that could be practically heated in the oven), giving a ratio of bend radius of bar diameter of *r/d* = 10. Each of the specimens (A,B,C) was designed with the same embedment length of 266 mm. To avoid surface effects, the first 25mm of the reinforcement from the loaded surface was not bonded to the concrete, by wrapping it with a bond break plastic tape.

Four conventional steel reinforcing bars were also provided between the pairs of concrete blocks; these were used to allow the specimens out of the heating oven without damaging the CFRP bars, and they were cut before the specimens were load tested.

Normal strength concrete with a 28-day strength of 30 MPa and tensile strength of 3.2 MPa was used

FRP Reinforcement Manufacture

Closed FRP loops were produce by wrapping a continuous carbon fibre tow around a mould (Figure 2). Each loop was made of 25 carbon tows, and the properties of these tows are shown in Table 1. The resulting fibre volume fraction of the 5´5mm cross-section reinforcement was 44%. Fyfe Tyfo-S epoxy resin was used to saturate the fibres to form the matrix of the composite.

The straight CFRP reinforcement was manufactured in the same manner as for the Group A and B loops. However, longer loops were made, so that the straight portions of reinforcement could be cut out.

After de-moulding the loops (Figure 3), they were sand-coated using fine glass sand bonded with epoxy resin (Figure 4). After an initial cure period, the loops were post-cured in a drying oven at 60°C for 12 hours. The glass transition temperature of the resulting CFRP was determined as T_g = 85°C (using dynamic mechanical analysis, and based upon tan d).

Figure 2. Filament winding the CFRP loops

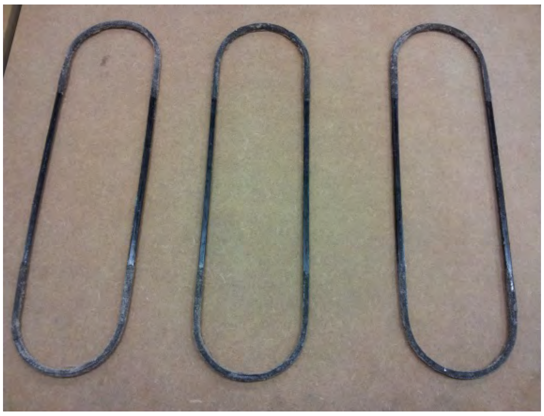

Figure 3. CFRP loops after de-moulding

Table 1: Properties of Carbon fibre tows

Fibre type	Number of Filaments	Strength (MPa)	Young's modulus (GPa)	X-sectional area (mm^2)	Elongation (%)	Filament diameter μm
Grafil 34-700WD	12000	4830	234	0.444	2.0	7

Figure 4. Sand coating a CFRP loop

Figure 5. Preparing a specimen for testing after taken out of oven

The Test Arrangement

Each type of specimen was either:

- tested unheated (ambient temperature);
- heated to the glass transition temperature of the FRP, T_g = 85°C, at which the resin is partially softened; or
- heated to well above the glass transition temperature, T_g = 130°C, at which the resin will be fully viscous and not active.

A thermocouple was cast into each specimen to record the temperature on the CFRP reinforcement near the centre of the concrete (see Figure 1), and an electric oven was used to heat the specimens to the required temperature within the concrete, over a period of 3 hours. The heated specimens were taken out of the oven, the steel supporting bars were cut, and the specimens were immediately loaded whilst still hot (Figure 5).

The loading arrangement was adapted from the ACI [9] and Canadian [10] guidelines that are used to measure the capacity of FRP bent bars and stirrups. The push-off specimens were placed on a low-friction bench adjacent the oven, and two 10 tonne hydraulic jacks were inserted between the concrete blocks. Jacking apart the concrete blocks causes the reinforcement to be pulled out from the concrete (Figures 1 and 6). The applied load was measured using an additional jack that reacted against a load cell.

The relative displacement of the two concrete blocks and the pull-out of the CFRP reinforcement form the concrete was measured using digital image correlation (DIC). The specimens were painted with a high-contrast pattern, and a series of images were captured at 0.2Hz using two high-resolution cameras, placed either side of the specimen (Figure 7). A bespoke DIC algorithm (GeoPIV, [11]) was used to track the movement of four pixel patches in these images, placed on the concrete and CFRP reinforcement on either side of the specimen (Figure 6). These patches allowed the FRP extension and slip to be determined. A particular advantage of DIC for these tests was that it can be quickly applied to heated specimens without any need for contact.

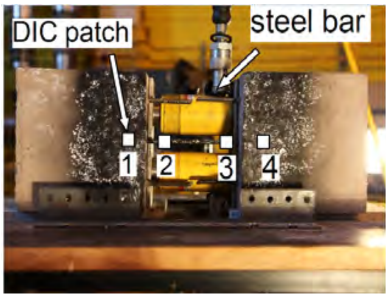

Figure 6. Test arrangement

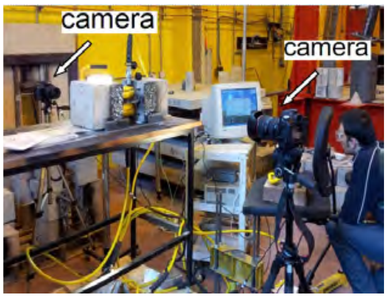

Figure 7. Position of cameras for DIC analysis

RESULTS AND DISCUSSION

Heating

Figure 8 shows a typical heating curve, during heating, and during loading for the reinforcement. The reinforcement temperature within the concrete lagged behind the gas phase temperature, and it took 3 hours to reach 130°C. During the loading test, the CFRP temperature dropped by 3°C, which is not a significant temperature drop.

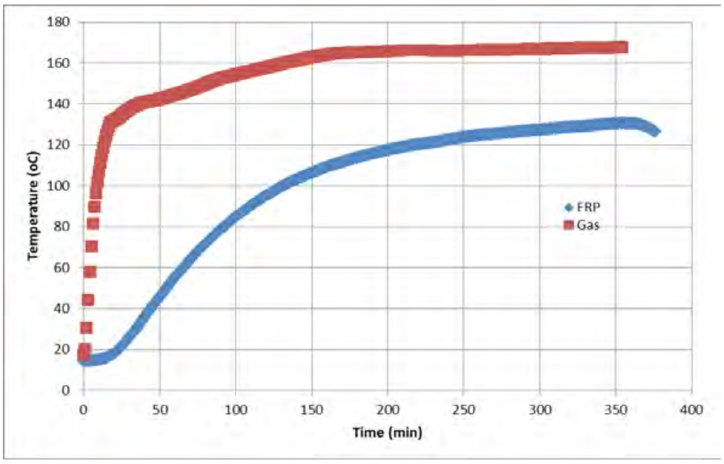

Figure 8. Temperatures recorded in the CFRP reinforcement and the oven gas phase during heating.

Reinforcement Stiffness

The change in distance between the patches on the free length of CFRP reinforcement (patches 2 and 3 in Figure 6) was used to calculate the strain in the reinforcement between the blocks. The fibre stress was calculated by dividing the load in each of the two stirrups by the fibre tow area (25´ 0.0444mm^2), and the resulting stress-strain curve for the Group A specimens is shown in Figure 9. The slope of the line in Figure 9 is 231.2 GPa, which is very close to the Young's modulus of 234 GPa given by the manufacturer (Table 1). This provides a check upon the experimental method, but also confirms that the stiffness of the CFRP is not temperature dependent, because it is governed by the fibres, and not affected by bond.

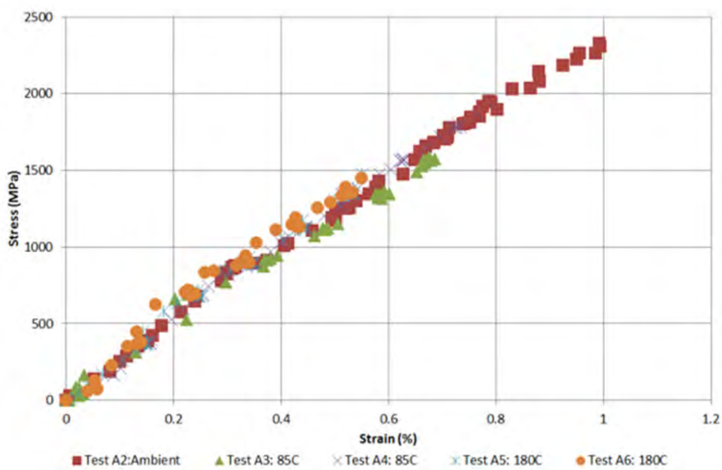

Figure 9. Stress strain response of the CFRP closed loops (Group A)

Load – Slip Responses

Figures 10, 11 and 12 show the pull-out response (load-slip) for the three groups of specimens. The slip was calculated as the difference in displacement between patches (1,2) and (3,4) in Figure 6. As patches 2 and 3 were a short distance away from face of the concrete, the strain in the CFRP reinforcement was used to slightly correct the slip results to take this into account. The load-slip figures are marked with a 25kN reference load, which is the yield load of a 500 MPa steel bar with the same cross-sectional area of the CFRP reinforcement.

Table 2 lists the failure loads, and the different modes of failure that were observed for all specimens. The specimens were sectioned using a diamond saw after the tests to investigate the failure modes, and these are illustrated in Figure 13 to 16.

The specimens containing straight bars (Group C, Figure 12), carried 32kN at ambient temperature, with one of the ambient specimens failing by CFRP rupture in the free (exposed) reinforcement length. Rupture in the free length of the reinforcement indicates that the reinforcement was sufficiently well bonded to the concrete for the reinforcement to reach its ultimate capacity. At elevated temperatures, the load capacity was greatly reduced, because the reinforcement pulled out of the concrete. This dramatic drop in the load capacity of FRP reinforcement due to resin softening is well documented in the literature [1,6,12,13].

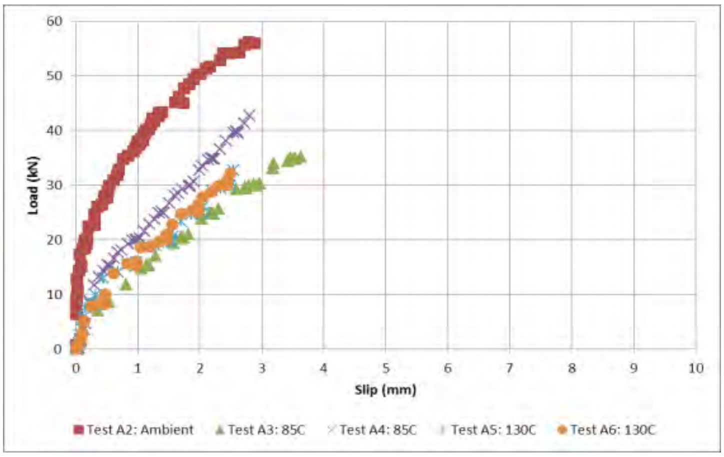

Figure 10. Load-slip response for Group A specimens
(The response for A1 was not captured due to an equipment failure)

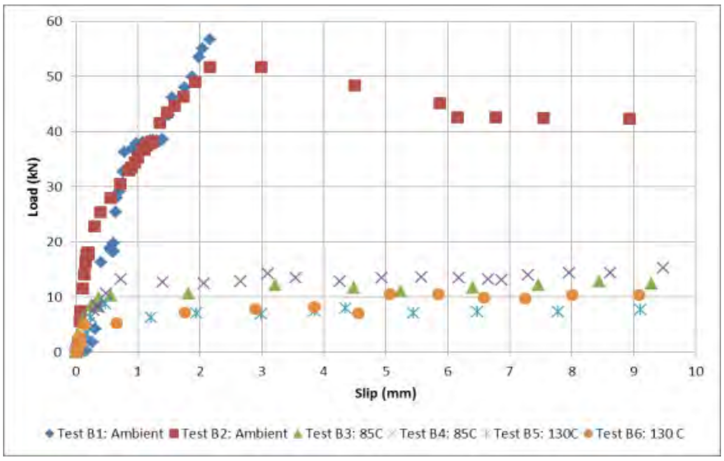

Figure 11. Load-slip response Group B specimens

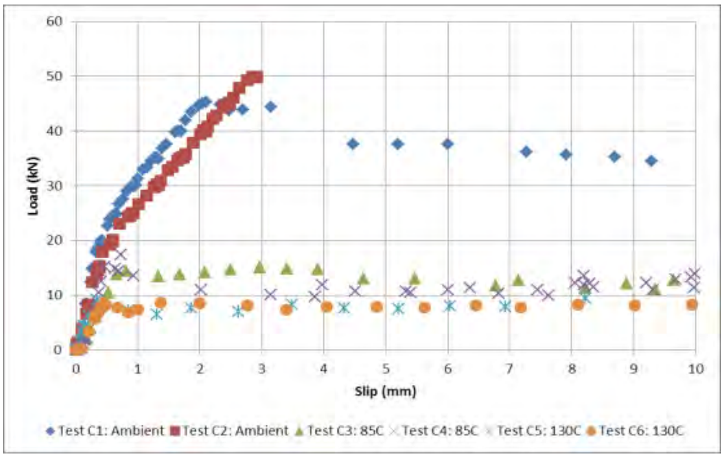

Figure 12. Load-slip response Group C specimens

Table 2. Test results

Temperature	Specimen Type	Test	Failure load (kN)	Average failure load (kN)	Failure mode
Ambient	A	A1	66.98	61.50	Rupture – in free length
		A2	56.20		Rupture – in free length
	B	B1	58.88	55.31	Rupture – in free length
		B2	51.74		Rupture – in free length
	C	C1	45.36	47.67	Pull-out
		C2	49.98		Rupture – in free length
T_g (85°C)	A	A3	35.16	38.96	Rupture – in free length
		A4	42.77		Rupture – in free length
	B	B3	12.81	14.01	Pull-out
		B4	15.20		Pull-out
	C	C3	15.09	16.27	Pull-out
		C4	17.44		Pull-out
130°C	A	A5	32.77	32.47	Rupture – within bond area
		A6	32.17		Rupture – within bond area
	B	B5	8.63	10.26	Pull-out
		B6	11.89		Pull-out
	C	C5	9.42	9.05	Pull-out
		C6	8.68		Pull-out

Figure 13. FRP rupture within the free length, A1 (ambient)

Figure 14. FRP rupture within the bonded area, A4 (130°C)

Figure 15. Pull-out of hooked FRP reinforcement, B4 (85°C)

Figure 16. Pull-out of striaght FRP reinforcement, C1 (ambient)

The Group B specimens (discontinuous loops or hooked bars) behaved in a similar manner to the straight bars, with little difference in the pull-out loads compared to Group C. Figure 15 shows pull out of the CFRP around the bent portion within the concrete.

The Group A specimens (with complete loops of reinforcement), however, successfully retained their strength capacity at elevated temperature, and failed by reinforcement rupture in all tests. Rupture occurred in the free reinforcement (Figure 13) for the ambient and 85°C specimens, but occurred within the concrete for 130°C (Figure 14). The stiffness of the response reduces, as is to be expected because of softening of the resin.

The superior elevated temperature performance of the continuous fibre loops compared to the discontinuous loops or straight bars is shown in Figure 17. The Group A specimens retained 37% of their ambient temperature strength at 130°C, as the continuous fibre was able to carry load despite the bond mechanisms being lost due to softening of the resin.

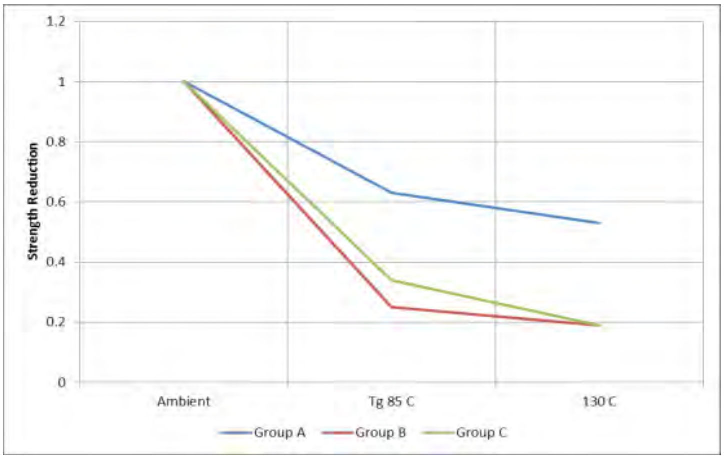

Figure 17. Strength reduction with temperature

Strength Reduction in a Curved FRP Bar

ACI 440.3R-04 [9] includes an equation to calculate the reduced strength of FRP bars at bends.

+ 0.3) ≤ (1)

f_{fb} = strength at bent up portion, f_{fu} = ultimate tensile strength, r = bend radius, d = bar diameter

For r / d = 50 / 5 = 10, as used in this study, this equation predicts that the bent portion of the FRP loop will be 20% weaker than the straight portion of the loop. The actual reduction in strength observed in the Group A specimens at elevated temperature was higher (37% reduction at 130°C). It is consequently not possible to account for the reduction in strength of these reinforcement loops based upon the bend geometry alone. Whilst Imjai et al. [14] have previously observed that the ACI equation can overestimate the bend capacity, it must be noted that a bixaxial stress state exists at the bend, where axial load, shear force, and transverse loads act. Furthermore, load-sharing will not be possible between the fibres in the loop at high temperatures.

The ACI equation does, however, suggest that using a wider and flatter loop would allow the loop reinforcement to carry additional load at high temperature.

CONCLUSIONS

In this study a new design of closed filament wound CFRP loops has been proposed. These were tested using push-off tests to determine how well the reinforcement performed at elevated temperatures, at and above its glass transition temperature, compared to similar specimens that contained straight bars, or CFRP that had been cut to remove fibre continuity.

At ambient temperature the FRP reinforcement in all but one specimen developed sufficient bond stress to give failure by rupture of the FRP outside the concrete block. The benefit of the CFRP loops became evident at elevated temperatures. Both straight and hooked reinforcement failed by pull-out at relatively low loads. Closed loops, however, retained strength up to three times more than the other specimens, and failed at a tensile strength that exceeded that of a steel reinforcing bar. The proposed design takes advantage of the fact that the FRP fibres are capable of sustaining a large proportion of their original strength at relatively high temperature (up to 1000°C for CFRP). When the interlock and friction mechanisms of bond force transfer are lost due to softening of the resin, tensile forces in the reinforcement (FRP fibres) can still be resisted through the loops. This new technology is promising and if developed might allow FRP reinforced concrete to be used in situations where its fire performance is important. It could help remove the last obstacle to its widespread use in buildings.

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